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SOME ASPECTS OF THE MECHANICAL TESTING OF NON-METALLIC SOLIDS

BY

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Abstract

Some problems associated with the mechanical testing of several classes of non-metals are reviewed. The difficulties encountered in measuring the elastic properties of rubbers, plastics and fibrous materials are considered and tests on the mechanical strength of glass-like materials are discussed. The significance of static and dynamic hardness measurements on non-metals is then considered in detail and the way in which such quantities as rebound hardness may depend on the conditions of test rather than on the properties of the material being investigated is described.

Introduction

The mechanical testing of non-metallic solids is an extremely wide subject and it is impossible in a short article to do more than indicate some of the problems involved. The present paper discusses those few aspects with which the author has personally become familiar rather than attempting, for example, to summarize the 6,000 pages which the current Standard Specifications of the American Society for Testing Materials devotes to this subject.

The ultimate aim in carrying out a mechanical test on a sample is to ensure that the material will withstand the

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stresses to which it is subjected in use without fracturing or seriously changing its shape. The tests themselves may, however, be carried out at a number of different levels, depending on the more immediate aim of the investigator. Sometimes, however, the product in its final form is tested by being subjected to the type of treatment which it is likely to receive; for example, a test which has been used by a firm of telephone manufacturers is to drop their instruments onto a hard floor from various heights and see whether or not they break. There is much to be said for this type of test, but it is clearly neither desirable nor even feasible always to adopt such a direct method of approach, and most mechanical tests involve making measurements under one set of conditions in order to find out what will occur under an entirely different set of conditions. This necessarily requires a knowledge of how the material behaves under various types of loading and consequently depends on a theory of its mechanical behavior. It is here that the mechanical testing of non-metals leads to special difficulties in that, whilst the behavior of metals in their elastic and plastic states has been investigated very thoroughly and a large reserve of both empirical and theoretical knowledge has been accumulated in the subject known to engineers as "Strength of Materials", the mechanical behavior of non-metals, which is very much more complex, has until recently received comparatively little attention.

Where all that is required from the test is to ensure that a batch of exactly similar specimens of a single material have approximately the same mechanical properties, many types of test are adequate, in that so long as the parameters measured are related, however remotely, to the parameters in which the investigator is interested, the test may be a workable one. An extreme example may perhaps be taken from the culinary arts, where the shade of brown of the top surface of a cake can be taken as an indication of the taste and texture of the interior. That this is not an infallible test must be well known to most who have attempted to practice the art as well as to many innocent victims.

The more removed the measured parameters in a test are from those which are really relevant, the greater is the possibility of error in applying such tests to materials for which there is no body of accumulated experience. Even when the physical measurements appear to be closely related to the properties which it is required to investigate, misleading results may sometimes be obtained from a failure to appreciate the exact significance of the test. Later in this paper some investigations by the author and his colleagues on the nature of dynamic and static hardness will be described to illustrate this point.

A more general approach to testing is that in which the relations between the measured physical properties of the material are correlated with its microscopic or chemical constitution. Whilst work of this kind, in so far as it is carried out at all, tends to be confined to the research laboratory rather than to the testing laboratory, in the view of the author it is only this more fundamental approach which can lead to a better understanding of the significance of physical tests and thus to an improvement of products as opposed to a mere sorting of them into those which conform to an often arbitrarily chosen standard and those which do not.

Classes of Non-Metallic Solids.

The different types of non-metallic solids to which mechanical tests are applied may be very roughly listed as follows:

(a) Plastics and Rubbers.

(b) Fibrous Materials (Paper, Wood, Textiles, etc.)

(c) Glasses

(d) Building Materials (Concrete, Stone, Cement, etc.) and Ceramics.

This classification is of course neither exhaustive nor free from overlap, but it is convenient in that many of the members of each group tend to have rather similar mechanical characteristics so that similar methods of test can be employed. It is proposed to mention briefly the type of mechanical properties associated with each group and discuss the particular problems which arise in carrying out mechanical tests on them.

(a) Plastics and Rubbers.

The outstanding difference between the mechanical behavior of these materials and that of solids built from simpler molecular units is the very much greater sensitivity of the former to the rate at which stresses are applied to them. Thus Young's Modulus for a steel wire could be determined either by hanging a small weight on the end and measuring the extension or by measuring the velocity of propagation of longitudinal elastic waves along the wire. The two results obtained would be found to agree within one or two per cent even when the stress cycle to which the material had been subjected was several hours duration in the former experiment and a very small fraction of a second in the latter. If the same experiments were carried out with a filament of natural rubber, the two values of Young's Modulus obtained would differ by a factor of perhaps a thousand. Similarly, the effect of temperature on mechanical properties is more marked by several orders of magnitude in high polymers than it is in non-polymeric materials. Consequently, mechanial tests carried out at one temperature and rate of loading in general give no indication at all of the mechanical behavior at a different temperature or a different rate of loading. In order to map out the mechanical behavior for a single polymer over a range of conditions, a vast amount of experimental work has to be carried out, as evidenced for example by the work of Nolle [1]* on buna rubber.

In carrying out tests to cover an extensive time scale a number of widely different experimental techniques have to be employed [2] and the range covered may extend from times of the order of days or months down to times of the order of 10^{-8} seconds.

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*Numbers in square brackets refer to Bibliography at the end of the report.

For the longer times ($>$ 1 second) the specimen is usually loaded mechanically and either its creep behavior under constant load, or the stress relaxation at constant extension is observed. For times of the order of one second down to about a millisecond, vibration methods can be employed. Either a specimen suitably loaded is set into free vibration or alternatively it is set into forced vibration by applying an oscillating stress. In the former case the period and the logarithmic decrement are observed whilst in the latter the mechanical behavior of the specimen can be deduced from the value of the resonant frequency of the system and the breadth of the reasonance peak.

At higher frequencies (corresponding to times between about 10^{-2} and 10^{-4} seconds) acoustical techniques are used, the propagation through the material of elastic waves generated by electro-acoustic transducers being observed and the mechanical properties deduced from the velocity and attenuation of such waves. The highest frequencies (up to 10^{8} cycles/sec.) are investigated by studying the propagation of ultrasonic pulses through the material.

For some high polymers it has been shown by Ferry [3] that a relation exists between the effects due to change in temperature and those due to change in the period of the applied stress. Where this relation holds, the task of investigating the mechanical properties is considerably lightened in that experiments need be carried out over only a restricted time range and an extended temperature range.

The classical theory of elasticity is based on Hooke's Law, which states that the components of stress and those of strain are linearly related. Further it is assumed that the strains are sufficiently small for powers higher than the first to be neglected. Neither of these assumptions is in general valid for high polymers. Strains large enough to invalidate the second assumption are quite usual in many polymers, whilst some of these materials, especially when they contain mineral fillers, do not appear to obey Hooke's Law even for extremely small deformations. Thus the treatment used in classical elasticity theory is in many cases no longer applicable and a new treatment is required to describe the stress-strain behavior of such materials. This aspect of the subject has received considerable attention in recent years and an admirable account of these and other problems of <u>rubber-like elasticity</u> will be found in the monograph by Treloar [4] on the subject.

(b) <u>Fibrous Materials</u>.

The fibrous material which has been longest in use is timber and a large amount of empirical knowledge has been acquired about its mechanical behavior. The mechanical properties of other members of this group such as paper, cotton, wool, silk, and the many new synthetic fibres, have been studies less extensively, but here again there is a large fund of empirical data. All these materials are composed of giant organic molecules and most of what has been said about high polymers in the previous section will apply to them. With these fibrous materials, however, there are two further factors which complicate mechanical testing.

First, these materials are often highly anisotropic, the mechanical response depending very markedly on the direction in which the stresses are applied (e.g. for balsa wood, Hearmon [5] states that the value of Young's modulus measured parallel to the grain is about sixty times as great as that measured tangential to the annual rings). Anisotropic materials require more than two constants to define their elastic behavior and for wood which approximates to the rhombic order of crystal symmetry nine independent elastic constants are involved. As, in general, all these constants are time-dependent, a complete investigation of the mechanical properties of a single sample of timber, even if it is confined to infinitesimal deformations, is likely to prove a long and difficult one.

The second complication in assessing the mechanical behavior of fibrous materials and especially of textiles and paper arises from the dependence of many of the properties on the mechanical interaction between fibres rather than on the inherent properties of the material of which the fibres are composed. For example, the energy lost in taking a specimen of a woven textile fabric round a stress cycle is partly due to internal friction within the individual fibres and partly to surface friction as fibres rub against each other during the deformation. Thus many of the properties may depend purely on the geometrical arrangement of the constituent fibres and it becomes extremely difficult to interpret the mechanical behavior of the finished product in terms of the properties of the material of which it is constituted or conversely to forecast the behavior of a fibre assemblage from measurements of the mechanical properties of individual fibres.

A further difficulty which arises with nearly all fibrous materials is the large effect that moisture content has on their mechanical properties. The water is in general intimately contained in the structure so that the materials have to be considered as two-component systems and any theories which do not include the role of the absorbed water will bear little relation to the practical behavior of the materials. A full account of the mechanical properties of wood and paper, much of which applies equally to other fibrous materials, will be found in the monograph by Barkas, Hearmon and Rance [5] which was referred to earlier.

(c) Glass and Glass-Like Materials.

At ordinary temperatures the elastic behavior of glass is very simple in comparison with that of most other materials. Unlike metals it does not show yield phenomena or plastic flow and unlike high polymers the strain produced is independent of the rate at which the stress is applied. It is in fact an almost perfect elastic solid which obeys Hooke's Law up to values of the stress at which it fractures and shows evidence of elastic after-effect only after it has been highly stressed for a considerable period of time. This is also true for most other vitreous materials so long as they are at temperatures well below their softening points and the measurement of elastic properties of this class of materials affords no special difficulty. At temperatures approaching the softening point viscous flow begins to take place and the viscosity of the material as well as its elastic modulus become important in assessing how it will behave under given stress conditions.

Most of the difficulties of investigating the mechanical properties of glass and glass-like solids are associated with the measurement of strength. As these materials are brittle and do not flow under the application of shear stresses the relevant quantity is in general the tensile strength. Now whilst considerable variations in tensile strength are observed with most solids, measurements with glass show an exceptionally wide range of values which depend on the manner in which the specimen has been treated and how the stress is applied. First the maximum stress which a specimen will withstand depends very markedly on the time for which the load is maintained. In the classical experiments of Grenet [6] similar specimens of plate glass were loaded for different times. It was found that when the loading time was forty hours fracture took place at less than half the stress required to produce it in a loading time of one second. Secondly, the presence of slight surface scratches can reduce the strength considerably and the value obtained for the tensile strength will depend very markedly on the surface condition of the specimen. Lastly, the size and shape of the specimen will influence the results and as shown by Griffith [7] the value of tensile strengths of thin glass fibres may be very many times the value found with larger specimens of the same material. The subject of strength of glass has in recent years received considerable attention and reference may be made to books by Morey [8], Haward [9], and Stanworth [10] on this subject. Some aspects in connection with hardness measurements are discussed later in the present paper.

(d) Building Materials.

This group, which includes granite, brick, slate, cement, concrete and the ceramics, covers so wide a range of mechanical properties that little of general interest can be said about methods of test. Nearly all these substances have very low tensile strengths and are normally used in compression. Young's modulus for most of these materials is of the order of 5×10^{10} dynes/sq.cm., but in the case of concrete the stress-strain relation is not linear, and a tangent modulus or a secant modulus has to be employed. Accounts of the mechanical properties relevant to engineering application are normally included in works on Strength of Materials such as that by Moore [11].

Hardness of Non-Metals.

In the previous section the mechanical properties discussed were quite well defined. Thus the meanings of the terms elastic modulus, tensile strength, etc. are clear for any given test and the difficulties arise only when the results obtained under one set of conditions have to be applied to a different set. In the present section the measurement of hardness will be considered and here we have the additional difficulty of trying to interpret the significance of measurements of this property before we can see how it is likely to be affected by changing the conditions of test.

Hardness is normally defined as the resistance which a body offers to surface indentation or abrasion by other bodies with which it comes in contact, and it is difficult to relate this property in a quantitative way to the simpler mechanical constants of the material. Thus indentation hardness can be measured by the load which has to be applied to an indenter to produce an irrecoverable deformation in the material under test and such deformations may occur as a result of plastic flow, fracture or tearing. There is also a second sense in which the term hardness is used and this is as a measure of the energy absorbed when the specimen is subjected to an impulsive load. This is called the rebound hardness and, as will be shown later, it may or may not be related to the indentation hardness of the material.

The theoretical treatment of hardness depends on the classical work of Hertz [12] who first calculated the distribution of stress between two elastic bodies in contact. The Hertz theory shows that the maximum shear stress does not occur in the region of contact but at a point some distance below so that if failure results from plastic flow under a critical shear stress this will begin below the surface at a distance of the order of half the radius of the circle of contact between the indenter and the specimen. For metals this is in fact what occurs and Davies [13] has shown that the static yield point of metals may be measured by pressing hard steel balls onto the surface of the metal under test and measuring the minimum load at which a permanent deformation is produced. Alternatively the experiment may be carried out dynamically and the minimum height of fall of the ball which produces permanent deformation may be measured.

In practical tests of hardness, such as the Brinell test, a fixed load is applied to the indenter and the radius of the indentation produced is measured. For metals this, too, can be correlated with the value of the yield point under shear stress [13] and thus bears a quantitative relation to a well defined physical property. The rebound hardness of metals is related to the work done in producing plastic flow in the metal and therefore also depends on the value of the yield stress of the material.

Most non-metals do not have well-defined yield points and many do not flow under the influence of an applied stress but fracture in a brittle manner when an indenter is pressed into them. Further, most high polymers show recoverable flow instead of, or in addition to, irrecoverable flow, and the interpretation of hardness measurements with non-metals is consequently very much more complex.

For indentation experiments with transparent high polymers the author [14] has used a photoelastic technique to show that both recoverable and irrecoverable flow take place. Whilst the recoverable flow is highly dependent on the time of loading, the irrecoverable flow, which occurs only at large loads, is associated with the non-linearity of the stress-strain relation at high stresses. Indentation experiments with glass specimens showed no evidence of flow and here fracture occurred in the region round the indenter where the tensile stress is a maximum. Since the stress field can be evaluated by Hertz's theory it might be thoughtthat the minimum indenter load which produced fracture could be simply related to the tensile strength of the material. This was first attempted by Auerbach [15] who found that the tensile strength calculated in this way was inversely proportional to $r^{1/3}$ where r is the radius of curvature of the indenter. This anomaly has been explained as being a statistical effect due to the flaw distribution in the specimen. The argument runs that with indenters of smaller radius of curvature the area of contact is smaller and hence the probability of finding a surface flaw in the right position to start a crack is reduced. Recent work [16,17] by two of the author's colleagues has shown that this explanation is incorrect and that whether or not a fracture is formed is normally governed by the availability of stored elastic energy in the specimen. Griffith [7] first pointed out that for a fracture surface to grow some of the stored elastic energy must be able to be converted into the surface energy of the new fracture area, and in indentation experiments this is generally the relevant criterion. Only when indenters of large radius of curvature are employed (> 10 cm. for steel indenters on glass) does fracture depend solely on a critical tensile stress being built up round the region of contact. Thus in indentation experiments on glass-like materials two distinct mechanical properties are involved. One is the tensile strength in the macroscopic sense, the other is the energy associated with forming a new fracture surface; in some tests it is one and in some the other that is being measured.

Measurements of rebound hardness are in practice carried out with an instrument called a scleroscope in which the height of rebound of an indenter is measured after the indenter has fallen a known distance. The principle of the method is that part of the kinetic energy of the indenter will be lost in plastic deformation of the specimen and hence the height of rebound will be a measure of the resistance of the specimen to indentation. Plastic flow is, however, not the only way in which the energy of the indenter may be dissipated. When the indenter hits the specimen stress waves are set up in the latter. Whilst for specimens of large dimensions the energy lost in this way is only one or two per cent of the kinetic energy of the indenter, the losses due to this effect may become considerable for specimens whose thickness is comparable with the dimensions of the indenter. Zener [18] has investigated this phenomenon theoretically and Tillett [19] has confirmed the effects experimentally. Only for specimens which are sufficiently large for the stress waves reflected from their boundaries not to have had time to return to the region of contact before the indenter and specimen separate, is the rebound height independent of the dimensions of the specimen. When the specimen is thinner, so that the stress wave is able to traverse the thickness of the specimen several times during the period of contact, the energy loss due to the flexural motion set up may be many times the losses due to inelastic behavior in the material; the rebound height then becomes a measure of the thickness of the specimen rather than of the physical properties of the material.

When precautions are taken to ensure that losses due to elastic waves in the specimen and to adhesion between the indenter and the specimen are small the results of rebound measurements on metal specimens can, as shown by Tabor [13] , be correlated with the yield strength and hence with the indentation hardness of the metal. For non-metals, in which plastic flow does not occur, the coefficient of restitution measured in rebound measurements must clearly depend on different physical properties. At the instant during the impact when the indenter is at rest its kinetic energy has been entirely stored in the form of elastic strain energy, partly in the indenter and partly in the specimen. In most practical cases the energy stored in the indenter is very small and the specimen is thus taken through a stress cycle the duration of which is equal to the duration of the impact and the coefficient of restitution is a measure of the fraction of energy lost in the cycle. This can be related [2] to the internal friction measured in other ways. Jenckel and Klein [20] and Tillett [19] have shown that for high polymers and organic glasses the observed coefficient of restitution is in fact a measure of the internal friction of these materials for sinusoidal stresses at frequencies equal to the reciprocal of approximately twice the time of contact.

Conclusion

It is hoped that the few examples discussed have illustrated the complex nature of the mechanical testing of non-metals and have shown that a proper interpretation depends on a fuller understanding both of the mechanical properties of these materials and of the theory of the tests. This is a field of enormous practical importance and one in which the physicist has a place at least as prominent as that of the engineer. The latter has perhaps rested too long in the comfortable belief that the accumulated body of experience on strength of materials will cover any testing problems he may encounter, whilst the former has too often assumed that all the important problems connected with properties of matter were solved at some time during the last century. With the advent of so many new materials and new conditions of loading, neither of these views is likely to prove tenable.

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